The current understanding of Biological Oxygen-Dosed Activated Carbon (BODAC) in removing organic compounds, pharmaceutically active compounds and heavy metals for water treatment

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Abstract

This study investigates the effectiveness of granular activated carbon (GAC) in Biological oxygen-dosed activated carbon BODAC filters for water treatment. GAC's porous structure and surface functional groups enable it to efficiently trap organic molecules and heavy metals. The biofilm on GAC plays a crucial role in contaminant removal by promoting the growth of bacteria. Adjusting flow rates and nutrient levels can regulate biofilm growth and enhance adsorption efficiency. Compared to other conventional wastewater treatment methods, BODAC filters demonstrate higher efficiency in removing organic compounds, pharmaceutical active compounds, heavy metals and also have desired attributes such as reducing biofouling, and minimizing bacterial growth, due to oxygen dosing. It shows promise as a sustainable solution for removing pollutants in water. Further research is needed to optimize biofilm control practices in water treatment processes.

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[1] Source for image: Abbenhuijs, 2023

Foreword: Water pollution necessitates effective and sustainable solutions. This literature review investigates the potential of Biological Oxygen-Dosed Activated Carbon (BODAC) filters for water treatment. By analyzing existing research, it aims to enhance our understanding of BODAC's efficiency in removing contaminants.

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List of Abbreviations

Abbreviation	**Definition**
AOC	Assimilable organic carbon
BAC	Biological activated carbon
BODAC	Biological Oxygen-dosed activated Carbon
DOC	Dissolved organic carbon
EAC	Extruded activated Carbon
EDI	Electro-Deionization Units
GAC	Granular activated carbon
MAP	Microbially accessible phosphorus
OTUs	Operational taxonomic units
PAC	Powder activated carbon
PhACs	pharmaceutically active compounds
RO	Reverse osmosis
UF	Ultrafiltration
WWTP	Wastewater treatment plant

Introduction

Pharmaceuticals and micropollutants in water are a growing problem that affects the quality of drinking water and poses risks to human health and the environment (World Health Organisation, 2012). Current methods for removing these contaminants are not effective enough, leading to their build-up in water sources (Verlicchi et al., 2012). This calls for the development of better water treatment techniques. We need alternative approaches that can overcome these limitations and provide more efficient and reliable water treatment solutions.

Biological Oxygen-Dosed Activated Carbon (BODAC) is a technology that can help address the challenges of removing pharmaceuticals and micropollutants from water. BODAC combines biological treatment with activated carbon adsorption, and might be a solution to improve water treatment effectiveness. BODAC uses specially prepared activated carbon that is covered with a biofilm consisting of different microbes. These microbes break down and remove the organic pollutants on the activated carbon, providing an extra way to remove contaminants. The combination of biological degradation and activated carbon adsorption in BODAC has the capability to enhance the efficiency of water treatment filters (STOWA, 2020).

This literature review aims to examine the current understanding of the application and effectiveness of BODAC in water treatment, particularly from a molecular biology perspective. By reviewing existing literature, we will assess the capabilities, limitations, and future possibilities of BODAC as a viable solution for tackling pharmaceuticals and micropollutants in water. To provide a comprehensive analysis, we will address the following three research questions: (1) How is BODAC prepared for water treatment? (2) What mechanisms influence BODAC's ability to absorb contaminants in water? (3) How effective is BODAC in different water treatment scenarios?

In the results all critical features of BODAC filters are evaluated with regard to the research questions. Their method of production is brought to light and the mechanisms of all components that contribute to water filtration. When the underlying finer mechanisms and their capabilities are examined, a better understanding of the functionality in different water treatment scenarios can be formed. These steps help to obtain a proper picture on the current understanding of BODAC filters. Two aspects that do not fall into the category of critical features, but are nonetheless important, are: ‘the data on the effectiveness of pollutant removal by BODAC (compared to a conventional WWTP and BAC)’ and the ‘costs and maintenance’ of the filters. These aspects contribute to the answering of the third research question.

Results

Working principle of BODAC filtration

The working principle of BODAC filtration involves the combination of activated carbon adsorption and biological degradation processes. In a BODAC filter, water passes through a bed of activated carbon, which has a high surface area and adsorptive capacity for organic compounds and other contaminants. The activated carbon traps and holds these contaminants on its surface. The biological degradation processes are facilitated by the biofilm on the activated coal particles. Metabolic processes of different microbiota degrade the pharmaceuticals and micropollutants, and desorb non-harmful products.

The utilization of biofilm-covered activated carbon filtration techniques is an established method employed in water treatment. To facilitate microbial activity, oxygen is dosed into the BODAC filtration system, which is not done in the established biofilm-covered activated carbon filtration methods. Oxygen can be supplied to maintain aerobic conditions within the filter bed. This ensures that the microorganisms have the necessary oxygen for their metabolic processes.

The combined effect of activated carbon adsorption, microbial degradation and Oxygen dosing in a BODAC filter results in the effective removal of organic contaminants from the water, improving its quality.

Critical features of BODAC filters

Granular activated carbon (GAC)

GAC, or granular activated carbon, is an activated carbon used for BODAC filters that consists of larger-sized carbon particles with a porous structure and high surface area. It is highly effective in adsorbing and removing contaminants from water. With its larger particle size, GAC provides optimal adsorption capacity and promotes the growth of biofilm. The GAC adsorbs pollutants whereafter the biofilm can degrade and desorb the non-harmful substances.

Production, adsorption and activity factors: Activated carbon is produced from environmental wastes with high carbon content. Lignocellulosic and coal materials have been used as raw materials planned for manufacturing of activated carbons. There are two approaches for preparing activated carbon that can be used in water purification processes: physical activation and chemical activation. BODAC uses the physical activation as it produces an activated carbon with a network of pores and with higher surface area that can adsorb organic molecules. The structure and the micro-pores of GAC, an AC type , are shown in ‘Figure 1’. A larger surface is also beneficial for more space for biofilm to grow. The activated carbon thus has good potential for adsorbing heavy metals because of its greater surface area, microporous ability, and chemical complexity of its external area (Asif Ahmad, Tauseef Azam. 2019). This type of activated carbon granules are in some literature referred to as L-type activated carbons. The surface functional groups of activated carbon are O–H, C=O, C–O, –CO3, C–H, and Si–H. The pollutants in the water or air come into contact with the activated carbon, and the attractive forces between the carbon functional groups and the pollutants cause them to adhere to the surface of the carbon particles. This process effectively traps pharmaceutical and biological pollutants (Mopoung et al., 2015). The primary method of pollutant removal in active coal filtration is adsorption, which is caused by London Dispersion Forces, a type of Van der Waals Force between molecules. Activated carbon's high surface area and network of pores allow it to effectively trap pharmaceutical and biological pollutants. Factors influencing adsorption efficiency include increasing molecular weight, a higher number of functional groups (such as double bonds or halogen compounds), and higher polarizability of the pollutant molecules due to electron clouds (Chemviron, 2023). The absorption of the activated carbon particles is the main contributor of removing pollutants in water treatment using Biological activated carbon (BAC) filters (Sbardella et al., 2018). The effectiveness of the adsorption of the active coal particles, according to Abromaitis (2018), largely depends on the following factors and characteristic: hydrophobicity, its physical form, charge, presence of micro- and macropores, adsorption surface area, the base material from which the carbon is made, the ratio of hydrophobic/hydrophilic components, the availability/concentration of components. Dissolved organic carbon (DOC) present in the water can act as a competing substance. DOC is hydrophobic and competes with other hydrophobic substances for available adsorption sites. Additionally, particles can block the macropores, resulting in fewer available adsorption sites.

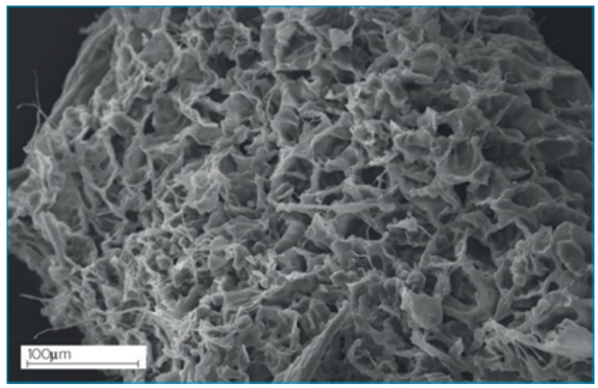
Activated Carbon (AC) type for Biological activated Carbon (BAC): Activated coal can be classified into different categories. Each has different sizes and applications, these can be seen in 'Table 1'. GAC is primarily utilized in BODAC filters (but also in other BAC filters), and can be utilized for liquid and gas phase applications. Liquid and gas phase applications in water filters refer to the treatment of contaminated water and purification of gasses or air. In liquid phase applications, water filters remove pollutants from water, while in gas phase applications, filters purify gasses or air by removing contaminants (Chemviron, 2023). GAC is used for BODAC filters. GAC is a specific form of AC used for water filtration. It differs from other ACs primarily in terms of its physical structure and application. GAC is characterized by larger particle sizes. The granular form of AC allows for better contact between the carbon particles and water, maximizing the adsorption capacity. The larger size also results in lower pressure drop and improved flow rates compared to other forms like powdered activated carbon (PAC). The choice between GAC and other forms of AC depends on the specific water treatment needs. GAC is more suitable for continuous flow systems and is often used in water treatment, drinking water filters, and certain industrial applications where longer contact times with water are required. BAC filters combine the adsorptive properties of AC with biological treatment processes. These filters employ a combination of AC and microorganisms to remove contaminants from water. In BAC filters, the choice of AC type depends on the specific contaminants targeted and the desired removal mechanisms (Huang et al., 2007). Both H-type and L-type AC can be used in BAC filters, but L-type AC is generally more common due to its broader range of pore sizes, which provides better adsorption capabilities for a wider range of organic compounds and dissolved substances. The mesopores in L-type AC allow for the colonization of microorganisms and provide an environment for the growth of biofilm, facilitating the biological treatment process in BAC filters (El-Barghouthi et al., 2007).

In short, AC is derived from carbon-rich environmental wastes and in BODAC filters, physically AC with a porous network and high surface area is used to adsorb organic molecules and heavy metals. The surface functional groups of AC attract pollutants, facilitating their removal through adsorption. The effectiveness of adsorption depends on various factors such as hydrophobicity, pore structure, and availability of adsorption sites. GAC is commonly used in BAC filters, providing efficient adsorption and supporting biofilm growth.

Figure 1: Microscopic image of GAC (Chávez et al., 2019).

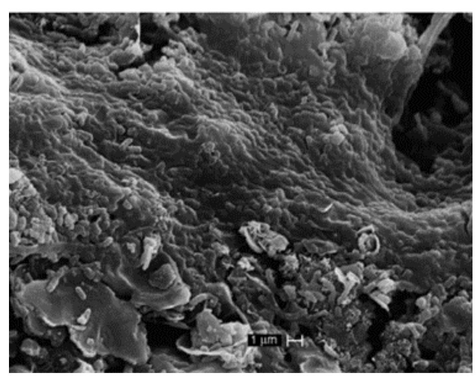
Type:	Size:	Phase application:
GAC	0.2 - 5 mm	Liquid and gas
PAC	< 0.18mm	Liquid and flue gas
EAC	0.8 - 5 mm	Gas phase

Table 1: Types of activated coal (*Chemviron, 2023*



Biofilm

Figure 2: Microscopic image of BAC (Simpson, 2008)



Composition and development: Biofilms are composed of microbial cells immobilized on the surface of GAC or embedded in the extracellular matrix (Ghosh et al., 1999; Lawrence and Tong, 2005) as seen in 'Figure 2'. Bacteria and fungi secrete extracellular polymeric substances that form a matrix of polysaccharides, proteins, nucleic acids and lipids (Goodwin and Forster, 1985; Horan and Eccles, 1986). Bacteria are the most abundant groups of microbes in BAC biofilms. Examples of bacteria commonly found in BAC biofilms include bacteria that utilyze nitrification Converting ammonia (NH3) to nitrate (NO3-) , denitrifying bacteria Removing nitrogen compounds from the water, oxidizing bacteria (involve the transfer of electrons from one molecule to another) and various heterotrophic bacteria capable of organic pollutant degradation (STOWA, 2020). The development of synthetic microbial consortia primarily relies on the various interaction patterns observed among microorganisms. These interactions encompass the exchange of small molecules, secreted by one species and utilized by another, as well as cell-cell communication mechanisms facilitated by signal molecule interactions (Ding et al., 2016). In later development stages, the control of biofilm thickness is relevant for its functioning. Controlling the amount of nutrients that are loaded into the biofilm is the obvious way to limit biofilm growth (Wang et al., 1995; Nishijima et al., 1992). Assimilable organic carbon (AOC) concentration is typically cited as the limiting factor for heterotrophic microbe growth in water (Van der Kooij et al., 1982). Additionally, it has been demonstrated that adding microbially accessible phosphorus (MAP) to GAC media increases both the amount of active biomass and bacterial colonization (Nishijima et al., 1997; Lehtola et al., 2002). In order to prevent an excessive growth of the biofilm, it might be necessary to reduce the flow rate of the water feed entering the BAC filter after an organic spill or discharge (where the concentrations of ozonated nutrients, such as AOC and/or MAP, entering the BAC filter may be very high). On the other hand, the BAC feed flow rate may need to be raised during times of low nutrient content to prevent reduction of the biofilm.

Microbe types and important metabolic pathways: LaParaet al. (2015) studied the composition of microbiota on BAC filters. In this study a method called Illumina MiSeq sequencing was used to analyze the biofilm. First they collected DNA samples and found 4.3 million sequences. Then they grouped similar sequences together and called them operational taxonomic units (OTUs). The bacterial communities they studied were diverse throughout the year of the study. When they compared the number of OTUs in each sample, they found that there were between 675 and 940 different ones. They found that there were around 1,200 to 1,800 OTUs based on one estimate, and 1,520 to 2,570 OTUs based on another estimate. The diversity of the bacterial communities remained fairly consistent throughout testing over a longer period. They found that while there were some variations, the most dominant bacteria in the biofilm is a type of bacteria called Nitrospira. Nitrospira is a nitrification utilizing bacteria. Nitrification is an important process in wastewater treatment plants that involves converting ammonia into nitrate. Two mechanisms are proposed in the literature. Both of them require oxygen. The first pathway mentioned is performed completely by Nitrospira, as it is proven that these possess all the necessary enzymes to catalyze the reactions (Caranto & Lancaster, 2017; Picone et al., 2020). These reactions are the following:

1. $NH_3 + O_2 + 2e^- + 2H^+ \rightarrow NH_2OH + H_2O$
2. $NH_2OH + H_2O \rightarrow NO_2^- + 4e^- + 5H^+$
3. $NO_2^- + 0.5O_2 \rightarrow NO_3^-$

The next mechanism, proposed by Mehrani et al., (2020), works with the protonated form of ammonia called ammonium. Just like the previous pathway, this one is performed completely by Nitrospira. This mechanism is composed of two steps, namely:

1) $NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+$
2) $NO_2^- + 0.5O_2 \rightarrow NO_3^-$

Nitrification in water treatment is desirable because, the excessive growth of algae and cyanobacteria, is a widespread and major aquatic problem caused by nitrogen in wastewater (Conley et al., 2009; Ge et al., 2014, 2015). The nitrogen removing aspect is important to remove nutrients for microorganisms. Biological nitrogen removal, which traditionally entails nitrification (and denitrification), is more efficient and economical than physicochemical procedures at reducing nitrogenous chemicals in wastewater (Ge, Wang, et al., 2015). Recent studies have shown that Nitrospira bacteria, rather than Nitrobacter, are the most diverse and abundant nitrite-oxidizing bacteria in BAC wastewater treatment plants (Koch et al., 2019). These bacteria were initially thought to only perform nitrite oxidation, but recent discoveries have revealed their broader metabolic capabilities. The comammox process, performed by these Nitrospira bacteria, including "Candidatus N. nitrosa," "Candidatus N. nitrificans," "Candidatus N. inopinata," involves the simultaneous oxidation of both ammonia and nitrite (Mehrani et al., 2020). It was previously theorized that a single microorganism could carry out both steps of nitrification, and subsequent discoveries confirmed this hypothesis (Dworkin, 2012). The growth conditions that favor complete oxidizers, such as comammox Nitrospira, are typically found in clonal clusters like biofilms, where there are low mixing and substrate diffusion gradients. Previous research demonstrated that Nitrospira outcompeted faster-growing nitrite-oxidizing bacteria in biofilms under conditions of limited dissolved oxygen, indicating their superior adaptation to low oxygen availability. The presence of comammox Nitrospira in environments with oxygen concentration gradients, such as the deeper zones of biofilms, can be attributed to this adaptive advantage (Mehrani et al., 2020). But in BODAC filters, where oxygen is abundant due to the oxygen dosing, the Nitrobacter would assumeable be more prominent than in the tests performed on BAC filters.

Activity influencing factors: The activity of the biofilm is not proportional to the fixed amount of biomass, but increases with biofilm thickness to a level referred to as "active thickness" (Kornegay and Andrews, 1968; LaMotta, 1976). At this stage, the distribution of nutrients becomes the limiting factor that distinguishes "active" biofilms from "inactive" biofilms. Therefore, stable, thin and active biofilms are advantageous in water and wastewater treatment. While measurements of total biofilm number provide information on the relative composition of BAC biofilms, they are insufficient to describe the activity and behavior of stable biofilms, as biofilm activity does not equal stable biomass. Therefore, the measure of biofilm activity (eg.biofilm and cellular components) allow better prediction and control of biofilm substrate removal efficiency (Simpson, 2008). Washout by the water can decrease the amount of biomass of the biofilm, as a result of hydraulic pressure (Piai et al., 2022). Other characteristic of the biofilm that impact the effectiveness for industrial use according to a study by Padmamperuma et al., (2018) include: degree of non-toxicity, capability of cohabiting, having similar growth rates, providing nutrients and/or stimulators to enhance growth, not causing under yielding effects, and delaying in growth, enhancing the capability of use multiple feedstocks, the capability of removing inhibitory molecules, and having the capacity of using microbial waste as a feed.

Biofouling in BAC filters refers to the growth and accumulation of microorganisms, organic matter, and other biological substances on the GAC (or within the filter bed) (Pinela et al., 2022). Biofouling typically begins with the attachment of bacteria, fungi, and other microorganisms to the surfaces of GAC. As these microorganisms multiply and form colonies, they produce extracellular polymeric substances that form a matrix of polysaccharides, proteins, nucleic acids and lipids, which are sticky compounds that can further promote the attachment of additional microorganisms and organic matter (Nguyen et al., 2012). Biofouling can negatively impact the efficiency of the BAC filter by reducing the available surface area for adsorption, clogging the filter pores, and interfering with the flow of water through the system (Pinela et al., 2022). Under certain conditions bioregeneration can occur in a BAC (Rattier et al., 2012; El Gamal et al., 2018). Bioregeneration is the process in which, due to the presence of microorganisms, the adsorption capacity is restored after the AC becomes saturated with contaminants. The microbiologically active biofilm in a BAC filter is capable of bioregeneration under suitable conditions (Abromaitis, 2018). Bioregeneration thus partly solves the issues caused by biofouling, as it cleans the blocking extracellular compounds.

Oxygen dosing

Bioactive carbon (BAC) filtration, while effective, can encounter challenges related to biofouling and unwanted bacterial growth, leading to filter clogging. However, the Biofilm Dissociation Activated Carbon (BODAC) method offers an additional feature that helps address these issues. By providing the biofilm within BODAC filters with sufficient oxygen, aerobic nitrification reactions can occur. These reactions break down undesirable biologic pollutants, stimulating bioregeneration and minimizing biofouling (STOWA, 2020).

In WWTP in Emmen, BODAC was implemented as a pretreatment method specifically to prevent biofouling of RO) membranes. Reverse osmosis (RO) membranes play a crucial role in removing contaminants from water, but they are vulnerable to biofouling. By applying BODAC as a pretreatment, the facility effectively removes nutrients that serve as bacterial growth sources, ensuring that no nutrients remain on the RO membranes. This preventive measure significantly reduces the risk of biofouling and ensures the membranes maintain their efficiency and longevity (Boorsma et al., 2020).

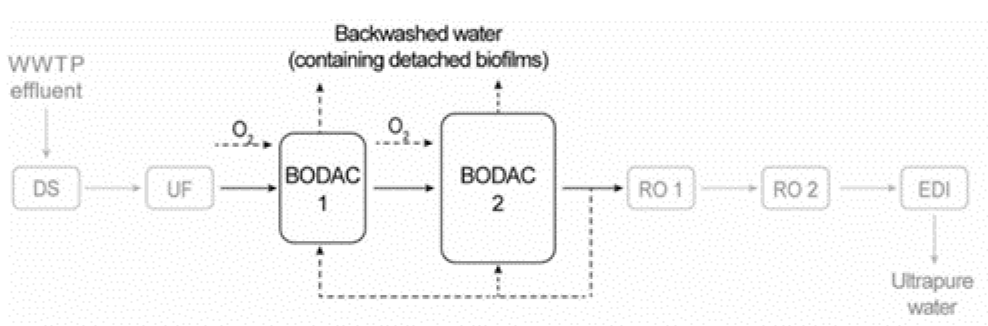
Example of the functioning of a water-treatment facility using BODAC filters

In ‘Figure 3’ the BODAC installation at the WWTP Emmen centraal is depicted in a flowchart. The input of the flowchart is water from a wastewater treatment plant (WWTP). The several components of the BODAC water treatment facility includes several essential components to ensure ultrafiltered water as an end product.

These components include: (1) Drum Sieve: The first line of defense in the treatment process, the drum sieve removes larger particles, such as leaves, debris, and sediment, from the water. This step ensures that subsequent treatment stages are not hindered by clogging or damage caused by these larger contaminants. (2) Ultrafiltration (UF): Employing specialized membranes with tiny pores, UFremoves even finer suspended solids, bacteria, viruses, and other microorganisms from the water (STOWA 2020). (3) BODAC filtration: BODAC filters use adsorption and microbial degradation to remove pollutants from the water. In the flowchart it is shown that the water passes through BODAC filters twice. In this particular water-treatment facility, the first BODAC stage takes 16 minutes, and the second 32 minutes. The use of two BODAC filters is, according to Van der Maas et al., (2020), to maximize the efficiency of removing pollutants. (4) RO Membranes: RO membranes play a vital role in removing dissolved salts, minerals, and various impurities from the water. Through a semi-permeable membrane, high-pressure forces water molecules across the membrane while rejecting impurities, resulting in purified water that meets strict quality standards (Veenendaal et al., 2019). (5) Electro-Deionization Units (EDI): After the RO process, electro-deionization units further purify the water by removing any remaining ions and impurities. EDI utilizes an electrical current to attract and remove ions from the water, resulting in ultrapure water suitable for specialized applications like pharmaceutical manufacturing or electronic component production (Veenendaal et al., 2019).

These aspects all together contribute to the treatment of water, ensuring its safety, cleanliness, and suitability for various purposes. Water treatment facilities can provide reliable access to high-quality water for domestic, industrial, and commercial use.

Figure 3: WWTP Emmen flowchart (Bernadet et al., 2023)

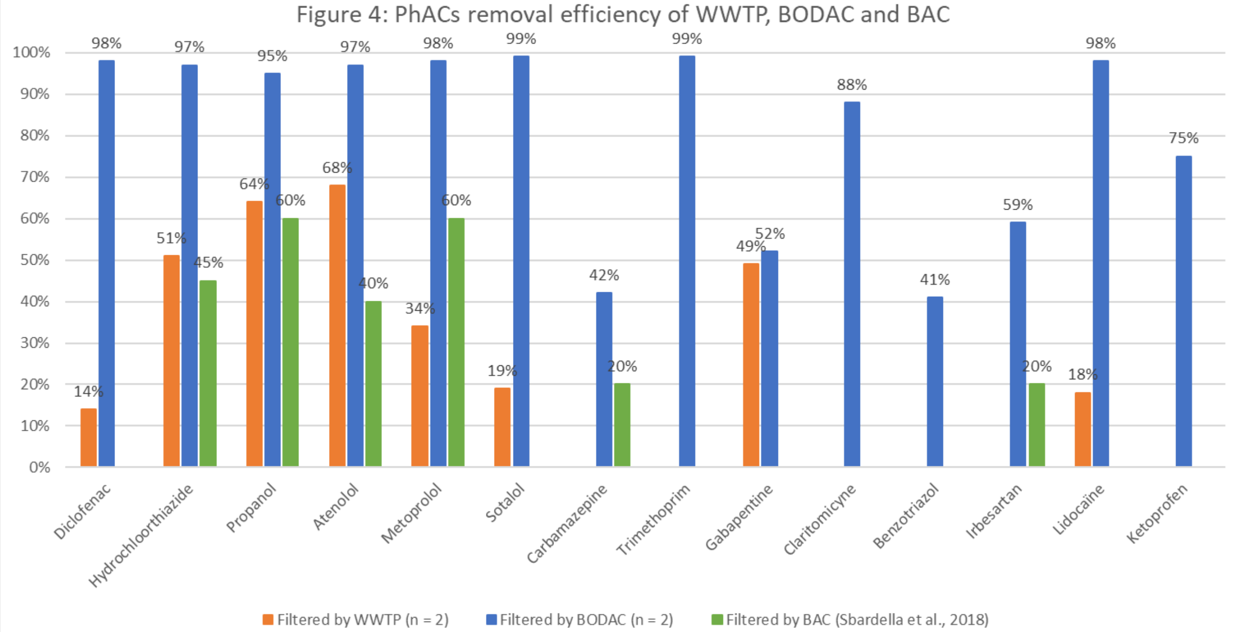


Comprehensive Considerations for BODAC Filter Systems

Effectiveness

To assess the effectiveness of BODAC filtration systems, data on removal of certain contaminants can be compared to BAC filters and conventional WWTP. A report by van der Maas et al. (2020) has compared the data (Figure 4) on the efficiency of removing pharmaceutically active compounds (PhACs). These results are promising as BODAC has a better removal efficiency on all the compared PhACs than BAC or WWTP. The primary mechanism for removing PhACs in BAC filters was found to be adsorption onto GAC. However, the presence of biological activity within the BAC filter resulted in higher removal efficiencies for some compounds compared to conventional abiotic GAC filters. The further improvement of efficiency can be due to oxygen dosing, which is the major upgrade from BAC. To optimize the efficiency adjustments can be made. Current biofilm control practices involve managing nutrient loading through flow rate and/or contact time, adjusting DO and pH levels in filter feed water, controlling the frequency of backwashing to remove biofilm nutrients and decayed microorganisms, and utilizing chemical oxidation. However, optimizing biofilm activity and controlling biofilm thickness in water treatment processes remains unclear (Simpson, 2008).

Figure 4: PhACs removal efficiency of WWTP, BODAC and BAC



[2]

[2] The data of this graph can be found in 'Table 2' on page 15

Costs and Maintenance of BODAC filers

The investment costs for BODAC are relatively high compared to alternatives such as biocide dosing. In Emmen, these costs can be amortized over the long term due to a long-term contract with NAM. Despite this relatively high investment, there are significant savings in operational costs. The replacement costs for RO membranes (which have not been replaced since the start in 2010) and the use of chemicals (no flocculants, fewer cleaning agents, and no biocides) are very low. This makes BODAC a sustainable and robust pre-treatment option for RO installations, particularly for wastewater reuse (Boorsma et al., 2020). The BODAC filter, including a microscreen, requires an investment cost of nearly 6 million euros (excluding VAT). Its annual operational costs amount to over 0.9 million euros, which is approximately €0.15 - €0.17 per cubic meter of water treated. This method assumes a 30-year linear depreciation for capital costs and includes maintenance costs based on a percentage of construction costs. Other costs include personnel, electricity, liquid oxygen, activated carbon, and disposal of backwash water. The total annual energy costs are €75,100, with an additional €13,000 for purchasing pure oxygen (STOWA, 2020).

The estimated costs for an Membrane Bioreactor range from €0.16 to €3.88 per cubic meter of water treated. It's important to note that these figures are based on 1995 prices and may vary depending on factors such as flow rate, treatment duration, influent and effluent requirements, iron and manganese concentration, vandalism protection, and market conditions. However, MBRs are not commonly used for treating contaminated groundwater, so up-to-date cost information specific to that application is unavailable. The costs for biological treatment using a biorotor system with a sedimentation tank range from €0.45 to €2.04 per cubic meter of water treated. These costs are indicative and depend on the pollution level and desired treatment outcome. This method is suitable for degrading mineral oil and BTEX compounds (Bodemrichtlijn, n.d.).

When selecting the most suitable and cost-effective water treatment method, it's crucial to consider factors such as treatment requirements, specific contaminants, and local conditions. The BODAC Filter requires a higher initial investment but has lower operational costs compared to MBRs. The biorotor system with a sedimentation tank is specifically designed for treating mineral oil and BTEX compounds. Evaluating these methods requires a comprehensive understanding of treatment needs and associated costs.

Discussion and Conclusion

Outline of the results: GAC is an effective adsorbent used in BODAC filters. It has a porous structure that can trap organic molecules and heavy metals by attracting pollutants through its surface functional groups. Factors like hydrophobicity and pore structure affect its efficiency. GAC is commonly used in BAC filters to promote biofilm growth and play a vital role in water treatment. Biofilms on GAC consist of microbial cells embedded in a matrix. Bacteria, including nitrifying, denitrifying, oxidizing, and pollutant-degrading bacteria, dominate these biofilms. The development and thickness of biofilms depend on interactions and nutrient control. Adjusting flow rates and nutrient levels can regulate biofilm growth. A study on BAC filters found diverse bacterial communities dominated by Nitrospira, which are important for nitrification. Two pathways for nitrification were proposed, both requiring oxygen. Biofilms also contain Comammox Nitrospira that can perform simultaneous ammonia and nitrite oxidation, indicating adaptation to low oxygen environments. BODAC filters with abundant oxygen may have a greater presence of Nitrobacter compared to BAC filters. Biofilm activity is influenced by thickness, nutrient distribution, and composition. Washout can decrease biomass, while biofouling in BAC filters affects efficiency. Bioregeneration can restore adsorption capacity by cleaning blocked compounds. The BODAC method addresses biofouling by providing oxygen, promoting nitrification reactions, and minimizing bacterial growth. Implementing BODAC as a pretreatment method prevents biofouling of RO membranes in water treatment facilities. The process includes drum sieving, UF, BODAC filtration, RO, and electro-deionization to ensure clean water for various applications. BODAC filters show higher efficiency in removing contaminants compared to BAC filters and sewage treatment. Biological activity and oxygen dosing contribute to this improvement. Optimizing biofilm control practices in water treatment processes is still uncertain. Despite the high initial investment costs, BODAC offers significant operational cost savings. It has low replacement costs for RO membranes and reduces chemical usage, making it a sustainable option for wastewater reuse.

Answers to the research questions:

1. How is BODAC prepared for water treatment? BODAC is prepared for water treatment by using GAC as an adsorbent in filters. The GAC's porous structure and surface functional groups allow it to trap organic molecules and heavy metals. Additionally, the biofilm that forms on the GAC plays a vital role in the treatment process. The biofilm consists of microbial cells embedded in a matrix and promotes the growth of bacteria, including nitrifying, denitrifying, oxidizing, and pollutant-degrading bacteria. The development and thickness of the biofilm can be regulated by adjusting flow rates and nutrient levels, enhancing the overall efficiency of BODAC in contaminant removal.
2. What mechanisms influence BODAC's ability to adsorb contaminants in water? The efficiency of BODAC in adsorbing contaminants is influenced by factors such as the hydrophobicity and pore structure of the GAC. The porous structure and surface functional groups of GAC facilitate the attraction and adsorption of pollutants. Additionally, the development and thickness of biofilms on the GAC, which consist of various bacterial communities, play a role in contaminant removal. Adjusting flow rates and nutrient levels can regulate biofilm growth and enhance adsorption efficiency.
3. How effective is BODAC in different water treatment scenarios? BODAC filters have shown higher efficiency in removing contaminants compared to other filtration methods

like BAC filters and sewage treatment. The presence of biological activity within BODAC filters, along with oxygen dosing, contributes to improved contaminant removal. The effectiveness of BODAC can vary depending on specific water treatment scenarios and the nature of the contaminants present. However, overall, BODAC has demonstrated promising results in addressing biofouling, promoting nitrification reactions, and minimizing bacterial growth, making it a sustainable option for water treatment with significant operational cost savings.

Gaps in the literature: The research on BAC and BODAC filters has found that there is no clear protocol for growing the necessary microbes that form the biofilm. As a result, the absence of literature on biofilm culturing implies that our knowledge regarding the cultivation of the bacteria required for biofilm formation remains limited, or that this information is not shared with the scientific community. However, ongoing studies are trying to find ways to understand and manage the biofilm better by looking at different indicators like physical-chemical, biochemical, and microbiological factors. They want to figure out how to optimize the biofilm and control its thickness during the water treatment process. In a study conducted in Emmen, it was found that the BODAC filters with oxygen dosing could be a promising technique for cleaning wastewater. However, in this study it is mentioned that there are still gaps in the knowledge on the mechanisms involved with the removal of PhACs (STOWA, 2020). It seems that both the breakdown of the residues by bacteria and their attachment to the filter play a role. This shows that the process is quite complex, and more research is needed to fully understand it. Overall, while BODAC filters show potential for treating wastewater, we still have a lot to learn. We need to figure out how to grow the right bacteria for the biofilm, understand how the filters remove pharmaceuticals, and consider other factors like the effects on the environment and the costs involved. This will help us use BODAC filters effectively and sustainably in water treatment.

Conclusion: The results show that using GAC in BODAC filters is effective for treating water. GAC's structure allows it to trap pollutants, and the biofilm that forms on it helps remove contaminants. Adjusting flow rates and nutrient levels can control the biofilm's growth, improving BODAC's efficiency. BODAC filters are better than other methods at removing contaminants. They reduce biofouling, promote helpful reactions, and limit bacterial growth, making them sustainable and cost-effective. However, more research is needed to optimize biofilm control. Despite the initial costs, BODAC saves money by reducing chemical use and membrane replacement. Overall, BODAC is a promising solution for clean water in various applications, including reusing wastewater.

Afterword: This research sheds light on the potential of BODAC filters for water treatment. I would like to express my gratitude to my supervisors, Sleutels and Scheffers, for their guidance and support. There is no conflict of interest regarding the findings presented in this research.

Component	**Removal by WWTP(n = 2)**	**Removal by BODAC (n = 2)**	**Removal by BAC (Sbardella et al., 2018)**
Diclofenac	14%	98%	
Hydrochloorthiazide	51%	97%	Ca. 45%
Propanol	64%	95%	Ca. 60%
Atenolol	68%	97%	Ca. 40%
Metoprolol	34%	98%	Ca. 60%
Sotalol	19%	99%	
Carbamazepine		42%	Ca. 20%
Trimethoprim		99%	
Gabapentine	49%	52%	
Claritomicyne		88%	
Benzotriazol		41%	
Irbesartan		59%	Ca. 20%
Lidocaïne	18%	98%	
Ketoprofen		75%	

Table 2: PhACs removal efficiency of WWTP, BODAC and BAC

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